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Software Support for Improving Technology Infusion

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Abstract

Previous experience has shown that the rate at which new technology is infused into space exploration missions has room for significant improvement. Impediments to successful infusion stem from imperfect formulation and communication of requirements, insufficient attention paid to the stringent engineering needed to demonstrate flight readiness, and lack of consideration of competitive alternative solutions. The "Technology Infusion Maturity Assessment (TIMA)" process has been developed to overcome these impediments.

The success of the TIMA process hinges on the combination of (1) human experts to provide knowledge, insight and guidance, (2) an organized method for conducting the assessment effort, and (3) customized software to support the process steps and human decision-making activities. The TIMA process has been used successfully at JPL for evaluating a variety of technologies, including hardware, software and combinations of both.

This paper focuses on describing the custom software tool, DDP, that was developed to support the TIMA process, and on showing how the needs of the TIMA process have influenced the development of the structure and capabilities of the DDP software.

1. Introduction

Previous experience has shown that the rate at which new technology is infused into space exploration missions has room for significant improvement. An informal survey conducted at JPL suggested that the predominant impediments to technology infusion fall into the following three areas:

1. **Requirements related:** the customer (mission) requirements were either miscommunicated, misunderstood, or under-defined.
2. **Readiness related:** the technology was deemed non-flightworthy in its current state of development (i.e., the technology was not considered for infusion into the flight design because of some unforeseen unresolved engineering issues).
3. **Competitiveness related:** other nearly-equivalent available technologies that can possibly substitute for the to-be-developed technology are now, or will soon become, available.

These findings indicate that technology infusion rates might be improved by establishing a clearer definition of the mission requirements, by identifying earlier the technology-specific engineering difficulties that may result from alternative technology/mission architecture decisions, and by improving knowledge of the projected status of the development of competing technologies from now to the estimated time of delivery.

The "Technology Infusion Maturity Assessment (TIMA)" process has been developed to fulfill these needs. It blends the use of human expertise, a disciplined process, and custom software support (Figure 1). We believe that the need to combine these three aspects recurs in almost every form of decision-making in space mission design, the very nature of which poses the following significant challenges:

- Cross-disciplinary concerns (e.g., spacecraft involves navigation, propulsion, telecommunications). These concerns are cross-coupled and interact in multiple ways (e.g., electromagnetic interference, heat transfer).
- Severe constraints on the systems being developed and on the development process itself. Time and budget

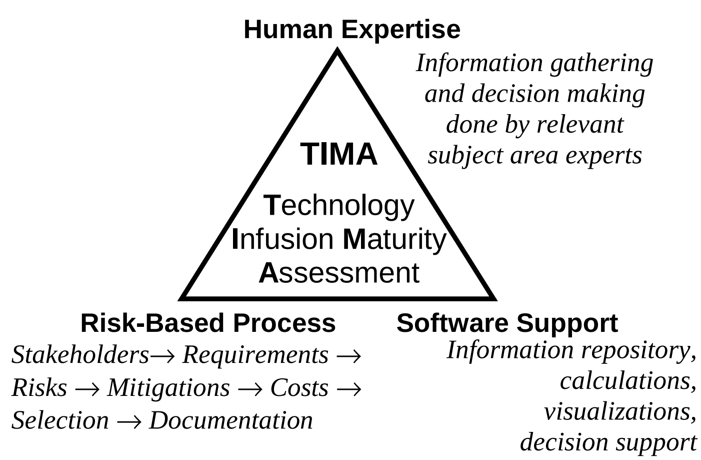

Figure 1. Expertise, process & software

pressures constrain development; operational resources constrain the resulting system (e.g., mass, volume, power).

- Mission-critical issues. Spacecraft are critical systems that must operate correctly the first time in only partially understood environments, with no chance for repair.
- Unknowns: past experience provides only a partial guide when new mission concepts are to be enhanced and enabled by new technologies of which past experience is lacking.

Because of these challenging aspects of space missions, usually no one person has expertise that spans all the disciplines, or can simultaneously juggle all the factors involved in large and complex designs. Furthermore, much of the design skill is "tacit knowledge" in the heads of spacecraft experts, so it cannot be encoded in an automated tool. Therefore, key decision making can be enhanced by a computer-aided, human-informed process.

The focus of this paper is on addressing these complex issues, and on describing the TIMA process blends human expertise, a methodical approach, and custom software support to yield successful computer-aided, human-informed decision making. The paper is organized as follows:

Section 2 describes the TIMA process, the risk-based reasoning methods that underpin it, and the role that custom software support plays in the process. Section 3 examines the process support aspects of the software. Section 4 discusses data gathering, data representation, and evaluative computation. Section 5 addresses formats for data visualization which provide technology area experts with a broad view of data details and results of computations. Section 6 looks at how the DDP software outputs can support the project decision-making process.

2. The TIMA process

2.1. TIMA origins

The TIMA process originated from Cornford's vision of a structured method for quality assurance planning of hardware systems [1]. At its core, the TIMA process yields a set of quality assurance activities that can be used as risk filters (i.e., the activities either reduce or remove risks that would otherwise threaten mission success). The risk-centric Defect Detection and Prevention (DDP) software tool [2] resulted from this vision.

Briefly, DDP relies on quantitative assessments of the relationships between three classes of information:

Requirements (REQs) (a.k.a. "Objectives" or "Goals") – the things the system needs to accomplish (includes constraints on its operation and development),

Failure Modes (FMs) (a.k.a. "Risks") – all the things that could occur that would negatively impact or limit the attainment of REQs, and

Preventative Measures, Analyses, Controls and Tests (PACTs) (a.k.a. "Mitigations" or "Solution Options") – all the things that could be done to reduce the likelihood and/or severity of FMs.

The quantitative assessments are of:

Impacts – the proportions by which the FMs, should they occur, will limit the attainment of REQs, and

Effects – the proportions by which the PACTs, should they be applied, will reduce FMs (and so lead to greater attainment of REQs).

Figure 2 shows the topology of how these concepts are connected. PACTs have associated resource costs (budget, schedule, mass, power, etc), and in most instances the sum total costs of all possible PACTs far exceeds the resources available. The DDP tool was formulated to aid in making decisions regarding which PACTs to apply to achieve maximal benefit for a given resource investment.

2.2. TIMA process for technology infusion

The TIMA process adapts the DDP tool to the study of technology infusion challenges. Its key steps are:

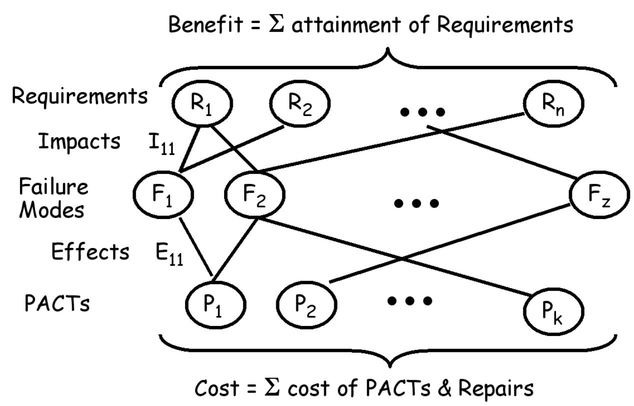

Figure 2. Topology of the DDP model

1. **Establishing the stakeholders in the technology**, i.e., those with the most to gain by infusion (e.g., flight project technologist, technology researchers themselves), and relevant subject area experts for the design, development and deployment of the technology (e.g., experts in avionics, packaging, manufacturing and test, experiment design, failure analysis, materials, quality assurance).
2. **Identifying the REQs that the technology must meet** before mission designers & managers will have adequate confidence to infuse the technology into a flight project. These encompass high-level mission REQs [e.g. schedule (e.g., an Engineering Model (EM) must be developed and thoroughly tested by 2005), size/mass limits], technology development REQs [e.g., evaluation of the

availability of all sources of such technology (incl. competitor technologies, surety that a satisfactory EM can be developed and thoroughly tested by 2005)], and detailed functional REQs that are specific to the required technology performance for its intended mission.

3. **Determining the potential, relevant** "**Failure Modes**", or risk elements – all the concerns that could negatively impact the desired functional performance of the technology as a result of issues that range from non-thorough definitions of design and performance REQs, to ineffective fabrication/ assembly materials and methods, to inadequate test processes for verification and validation of the specified performance/reliability of the product, and to shortcomings of programmatic and institutional resources and/or infrastructure. Also done in this step is an assessment of *how much* each FM can affect the REQs (i.e., what proportion of a given REQ will be lost if the FM occurred). The aggregation of this information identifies "tall pole" FMs – those that most threaten the REQs.
4. **Identifying PACTs that can reduce the risk of failure.** PACTs include practices and procedures involving design, fabrication, assembly and functional characterization by testing or diagnostic exercises that most likely will be required for advancing the flight technology. Also done in this step is an assessment of how effective each PACT will be in reducing each FM (e.g. chance of detecting or preventing the FM).
5. **Generating a rough estimate of the cost of implementing each identified PACT.**
6. **Using the DDP tool to perform Risk Balancing calculations.** This step helps to determine which are the tall tent pole items that, when addressed, will buy down the most risk. This step also helps define optimal Cost/Benefit funding recommendations which increase technology infusion success.
7. **Documenting and reporting the TIMA findings** and suggested recommendations for stakeholders.

2.3. Software support for the TIMA process

The TIMA process is conducted by assembling the group of stakeholders and technology area experts in a series of facilitated meetings in which they perform the information gathering and decision-making steps listed above. Software support is used to capture the information on-the-fly, to make calculations in terms of the gathered information, to visually present the results, and to aid project experts in their decision making. In practice, the DDP software is kept running throughout the duration of the meetings, displayed on a single screen visible to all.

The software built for the original DDP process [3] has been used in several TIMA studies, and gradually has been extended as the nature of those studies became better understood. The need for software support derives from the quantity and inter-connectedness of the information involved. For example, the most recently completed TIMA study ended with 29 REQs, 58 FMs, and 36 PACTs (the study recommended 25 of these PACTS for implementation). Connecting these elements were over 600 quantitative Impact links and almost 300 quantitative Effect links. Figure 3 shows the topology of the actual data from this recently completed study. Using DDP software support it is practicable to convene a TIMA group comprised of 5 to 20 experts, and, during 3 or 4 half-day meetings, gather the information needed for analytical decision making

Next, we consider information technology challenges in building/extending software to support space missions.

3. Flexible process support

As described in Section 2, TIMA sessions are run as facilitated face-to-face meetings. The number of experts contributing in these sessions ranges from 5 to 20. The facilitator needs to be a person having overall familiarity with the technology being assessed as well as knowledge of the TIMA process. The facilitator may or may not be

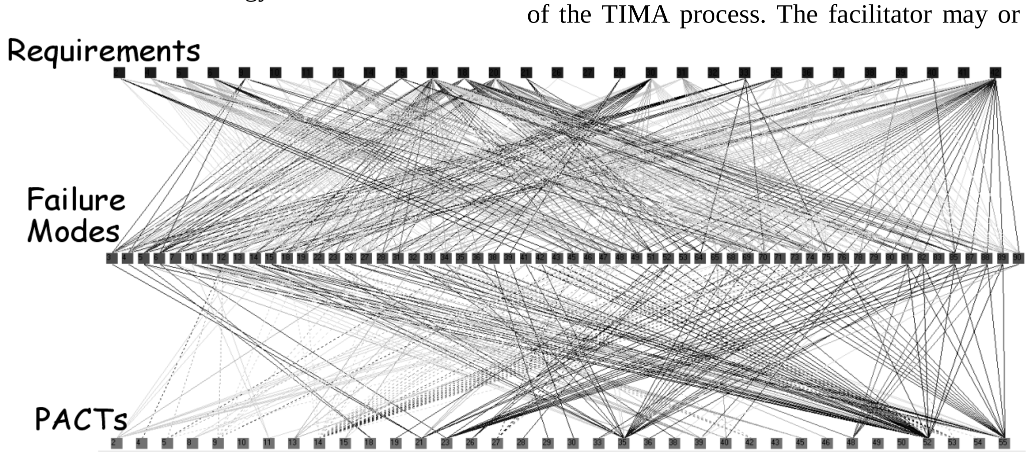

Figure 3. Topology of data in a completed

the person “driving” the DDP tool (i.e., controlling the tool through keyboard and mouse).

The DDP software lends flexibility to the TIMA process, but does not try to control it in a “process programming” sense. Figure 4 illustrates the interactive roadmap which shows the main activities of the TIMA process and indicates the order in which they are typically performed. By clicking on one of the colored boxes of this roadmap, the display shows a screen layout appropriate to that box. For example, by clicking on the FM box, a screen layout with the FM tree window is displayed along with the property editor window (for viewing and setting detailed properties of an individual FM) and the bar chart window (see Figure 5).

The software provides users the flexibility to deviate from the waterfall model nature of the TIMA process. For example, while entering FMs, users may “leap ahead” in the process to enter the PACTs that they know will reduce

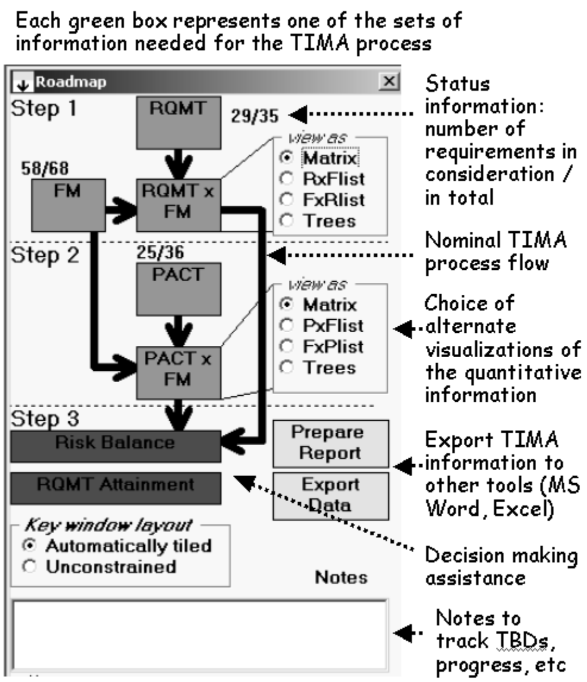

Figure 4. Roadmap view for TIMA process

the likelihood of those FMs (rather than waiting until they may have forgotten about that PACT). Similarly, users may return at any time to any process step to add something that was previously overlooked. Thus, the DDP tool was designed to allow wide process flexibility.

4. Data issues

4.1. Conceptual data.

When Cornford first envisioned the DDP process, he experimented using Microsoft Excel® spreadsheets to explore the utility of the process. The initial results proved promising and thus motivated the subsequent development of the custom DDP support software.

The core DDP data structural elements are:

- *trees* for organizing the concepts (REQs, FMs and PACTs) into hierarchical structures,
- *relationships (links)* between the concepts (Impacts between FMs and REQs, and Effects between PACTs and FMs), and
- *detailed attributes* for identifying *titles* for tree elements, *numerical values* for the relationships, and *descriptions* and *notes* of REQs, FMs and PACTS

These core structural elements have evolved through use of the DDP tool in recent TIMA sessions, motivating the creation of new extensions to the core structure. For example, new attributes that have been recently added are:

FM categorization – in addition to FMs being organized within a hierarchical tree structure, TIMA studies induced a need to separate FMs into categories of:

“general” (e.g., life/wearout issues)

“technology” problems that fall within the purview of the researchers who developed the novel technology (e.g., susceptibility of the new technology to radiation, and what to do about it),

standard “engineering” concerns that are usually handled through application of standard flight development practices, and

“both” (problems that span both technology and engineering). The "both" category is especially important, since resolution of FMs in this category usually requires continual collaboration between technologists and design engineers. Thus, the FM data entry format was extended to include a “Category” attribute which could accept inputs from a user-defined set of possible values.

Assigning time phase attributes to applied PACTs – TIMA studies typically result in an identification of the major risks associated with the technology being assessed, and in the selection of PACTs that, in combination, are

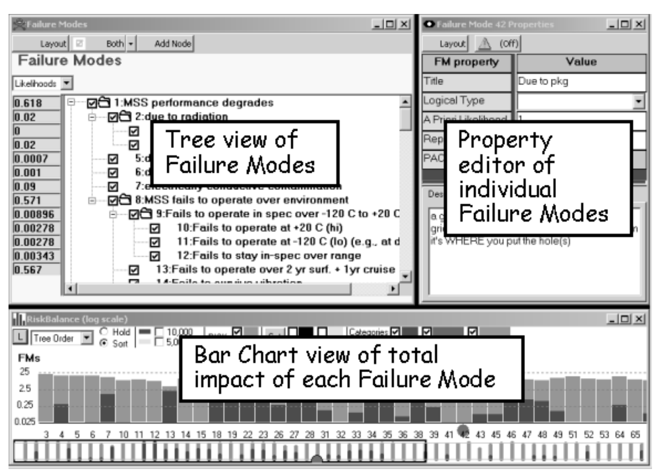

Figure 5. Screen layout for a particular step

expected to reduce those risks to acceptably small levels. It is often useful to know the progression of risk reduction as PACTs are applied; plans that reduce risks early in the technology development process are much preferred to those that reduce risks late in the process. Thus, the PACT data entry format was extended to include a "When" attribute which could accept inputs from a user-defined ordered list of time values (e.g., project phases, or financial quarters).

Note the synergy between these two DDP data entry format extensions; plans that reduce those risks stemming from "technology" FMs late are especially risky since the greatest uncertainty in the entire process concerns the status of the technology development of novel technologies.

The above examples of addition of TIMA-motivated extensions to the DDP software are similar and, from a data processing perspective, straightforward; all that is needed to implement the extension is the addition of a new attribute to the data schema.

Ensuring that TIMA data generated using earlier versions of the DDP tool is "upwards compatibility" with later versions is also straightforward. Generic mechanisms (such as the property editor) can readily accommodate addition of new attributes. Of course, when new attributes are added, other aspects of the DDP tool may need more attention, notably mechanisms for visualization and calculation (see subsections 3.3 and 3.4).

4.2. Data representations.

The data representation models that are generated by the DDP software were developed with typical time- and space-efficiency considerations in mind. By computer science standards, TIMA applications manipulate only a modest quantity of data; the three trees of information contain several hundred nodes in total, while the connective links among them may number a thousand or so. While DDP software is running, the tree structure information and many of the attribute values are held in RAM. Textual attributes (descriptions, notes, etc) with potentially voluminous and unbounded length, are read into RAM on an as-needed basis.

The DDP software automatically computes aggregate information of utility to the TIMA process. For example, for each FM, DDP computes the sum total Impact on REQs by summing, for each REQ, the product of: the REQ's weight, the quantitative Impact value that that FM has on that REQ, and the likelihood that that FM will occur. This sum total Impact can be calculated for the full range of conditions from where any or all PACTs are turned off (which effectively ignores the effects of applying turned off PACTs), to where all PACTs are turned on (the optimal situation where all PACTs are applied).. Recall that applying a PACT serves to reduce the likelihood and/or impacts of FMs by the value assigned to the quantitative PACT Effect link.

From a REQ perspective, computations yield measures of how much each REQ is at risk. From a FM perspective, computations yield measures of how much risk each FM contributes. From a PACT perspective, computations yield measures of how much benefit is to be gained from applying each PACT.

Overall computations of benefit (i.e., sum total attainment of REQs) and cost (i.e., sum total cost of applying selected PACTs including implementing repairs to the problems they detect) yield measures of how various PACT selection sets impact the problem as a whole.

During the data collection portion of the TIMA process, it is important that the software be able to respond rapidly (i.e., there is no substantial "wait state" between data entries). Frequent re-computation of the sum totals of the Impact and Effect measures listed above could significantly slow down software responsiveness. To preserve rapid responsiveness, the DDP software uses standard techniques for improving efficiency including: 1) caching of frequently used inter-mediate results, 2) performing re-computation incrementally (when a change occurs, re-compute the ripple effects of only that change rather than re-computing everything from scratch), and 3) limiting the computation to only those elements displayed in currently visible windows. Together, these standard efficiency-improving techniques suffice to retain adequate responsiveness for the quantity of data typical of TIMA studies. During a TIMA session, after making a change to one of the numerical Impact or Effect values, or a change to the current selection of PACTs, re-computation and redisplay takes under a second running on a typical modern PC.

5. Visualizations

Much of the effort of building the DDP software has gone into the construction of the graphical user interface (GUI). Human input, scrutiny and guidance pervade the TIMA process, so the software tool's GUI is obviously of critical importance. Furthermore, the TIMA process yields a combination of inputs from multiple experts. While the amount of information collected during TIMA sessions is modest from a data processing perspective, it is a challenge for humans to absorb it all at once. In fact, it is far more information than can be presented on a single screen. This section discusses the ways in which the DDP software addresses the visualization challenges. First, we summarize DDP's general approach to visualization, then we focus on visualization and the TIMA process.

5.1. DDP's general approach to visualization.

The concept of using multiple views to illustrate complex and voluminous amounts of information is now familiar to many people thanks to the popularity of UML and the tools that support it. In the requirements engineering setting, tool-supported multiple views were pioneered in the Knowledge-Based Requirements Assistant (KBRA) [4]. Similarly, DDP offers several key display views of its data concepts:

- *Trees* for the hierarchies of REQs, FMs and PACTs.
- *Matrices* of numbers for the quantitative Impact links between FMs and REQs, and for the quantitative Effect links between PACTs and FMs.
- *Bar charts* for the results of aggregate calculations (e.g., each FM's sum total risk to REQs).

DDP employs a variety of techniques to support users working with its multiple display views:

- Uniform color conventions apply across (nearly all) the views to indicate the type of information (e.g., by default, red is used for FMs, so a red-highlighted row in a Matrix indicates it corresponds to a FM, a red folder icon in a tree indicates it portrays a collection of FMs, etc).
- A notion of “focus” draws users’ attention to the items currently under scrutiny (e.g., in the tree view, colored icons draw attention to the current item and its ancestry in the hierarchy; in the matrix view, the row and column that triangulate to the current item are highlighted). Thus when users switch views, they can quickly relocate the current item in the new view.
- Views are automatically kept in correspondence (e.g., when a sub-tree is “collapsed” in the tree view so that only the root of that sub-tree is left visible, a matrix view’s rows/columns corresponding to the elements within that sub-tree are replaced by a single row/column whose values correspond to the aggregate values for that entire sub-tree). When possible, visual cues alert users to the status of information in a view (e.g., users of Windows-like trees are familiar with the little boxed + and – symbols that indicate collapsed and expanded sub-trees respectively; in the DDP software, these same symbols also annotate bars on bar charts and header cells on matrices).

Individually these are small and barely noticeable factors, but their cumulative effect renders the multiple views attribute much more user-friendly. This applies not only when switching between screens, but also when using multiple views in the same screen.

At any one time, only some of these multiple views will be visible. Section 3 discussed how the software can suggest a view (or views) that are appropriate to the process step that is underway.

5.2. Visualization customization, and custom visualizations.

Trees, matrices and bar charts are in widespread use for displaying many forms of information, and so are immediately familiar to most TIMA participants. However, implementing the features mentioned in the previous subsection often necessitates some customization of these standard GUI elements.

The TIMA process has motivated the design of some new custom visualizations that typically must be constructed from low-level graphic elements. Several examples follow, which, while quite different in form and content, share the goal of seeking to display as much information as possible in a concise but intuitive manner.

DDP’s risk region chart (Figure 6) is similar to the risk charts seen in many risk tools and presentations of risks. The likelihood and impact (on REQs) of each of the FMs are calculated, and these values are used to locate a small square representing that FM on the 2-D chart. The axes of the chart are impact and likelihood plotted using a *log* scale. As a result, straight diagonal lines indicate constant risk. DDP lets users position such lines to demark regions

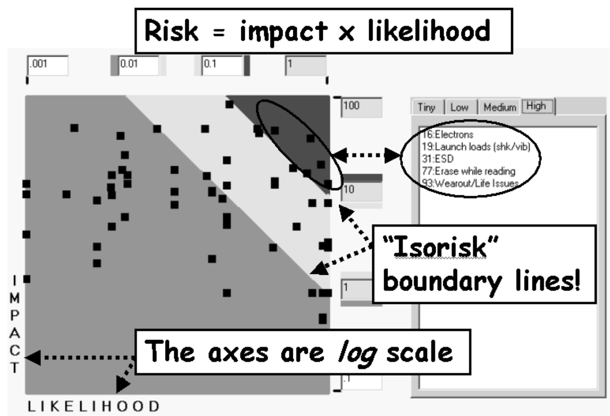

Figure 6. DDP’s risk region chart

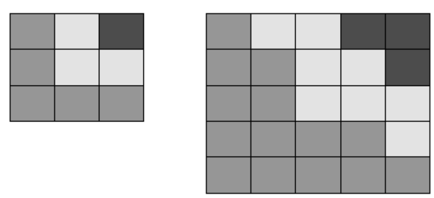

Figure 7. Regions in traditional risk

of “high”, “medium” and “low” risk. Figure 6 shows these regions colored in the traditional “traffic light” color scheme, where red indicates high, yellow medium, and green low risk. We note that the stair-step boundaries on traditional risk charts, whose scales are linear rather than log (Figure 7) are approximations of our “isorisk” boundary lines

DDP’s “stem-and-leaf” chart (Figure 8) shows sparse matrix information in a compact form. Denise Howard had the idea to use this view for presenting risk mitigation information in the Risk Balancing Profile (RBP) tool, and her design was prototyped by Chris Hartsough. RBP had a

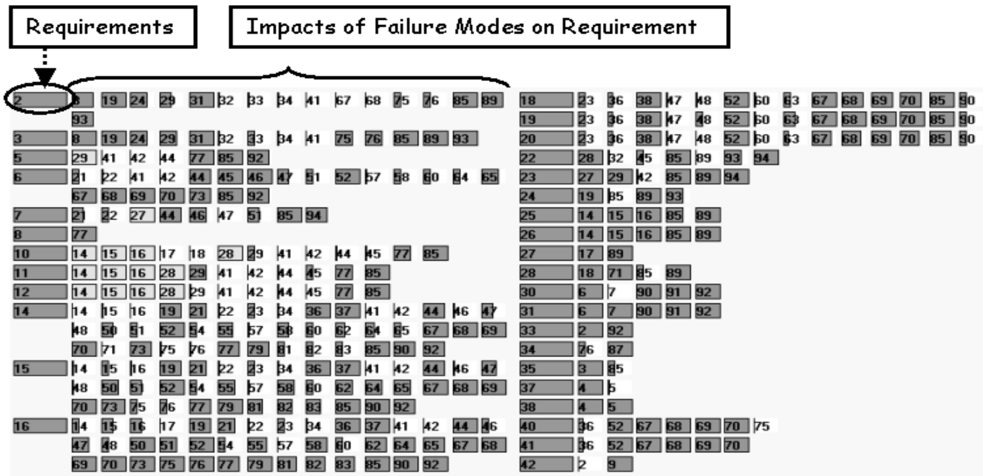

Figure 8 Stem-and-leaf chart of sparse matrix information

much simpler representation of risk mitigation than DDP/ TIMA. In RBP, mitigations either reduce risks, or they don't – there is no attempt to capture by how much a mitigation option reduces a risk. In Howard's GUI design for RBP, risks are listed, and listed alongside each risk are all the mitigation options that reduce that risk (and in an analogous view, mitigation options are listed, and listed alongside each one are all the risks that they reduce). We adopted this idea for DDP. We adapted this idea to indicate quantitative information by using colored boxes whose lengths are proportional to the quantity of Impact or Effect. We extended the idea to work with larger amounts of information – a long list of items is wrapped over more than one line; information is organized into several major columns; and when there is too much information to fit on one screen, scroll buttons appear. Figure 8 shows an example. The blue boxes represent REQs. Alongside each REQ are listed all the Impacts of FMs on that REQ – the number in the cell refers to the FM, while the horizontal dimension of the orange-colored box is proportional to the magnitude of that Impact. We embedded RBP within DDP, and arranged for RBP information to flow into DDP proper [3].

A thumbnail slider control is used on bar charts as a replacement for the standard slider control on large bar charts (Figure 9). The entire bar chart in miniature takes the place of the typical slider bar's rectangular area, with the visible portion boxed. This box can be slid horizontally using the mouse, just as one would slide a slider in the traditional control. The effect is to bring into view, in the full-scale bar view, the portion now indicated in miniature in the slider's box.

Each of these views strive to show as much information as possible in the space available, and in the style advocated and illustrated in TUfte's works (e.g., [5])

6. Assisted decision making

Making well-reasoned decisions in the selection of an optimal set of PACTs can be a major challenge. PACTs, FMs and REQs are highly interconnected (recall Figure 3), and the selection of each PACT is an independent decision – if there are N PACTs, then there are 2^N ways of selecting among them. Essentially, this is an *optimization* problem. If costs are capped, then the optimization problem involves finding the PACT set that maximizes the benefit (attainment of REQs) without exceeding the cost cap (the total cost is the sum of the costs of the selected PACTs and the FM repairs they induce). If there is a minimal acceptable science goal then that goal sets the

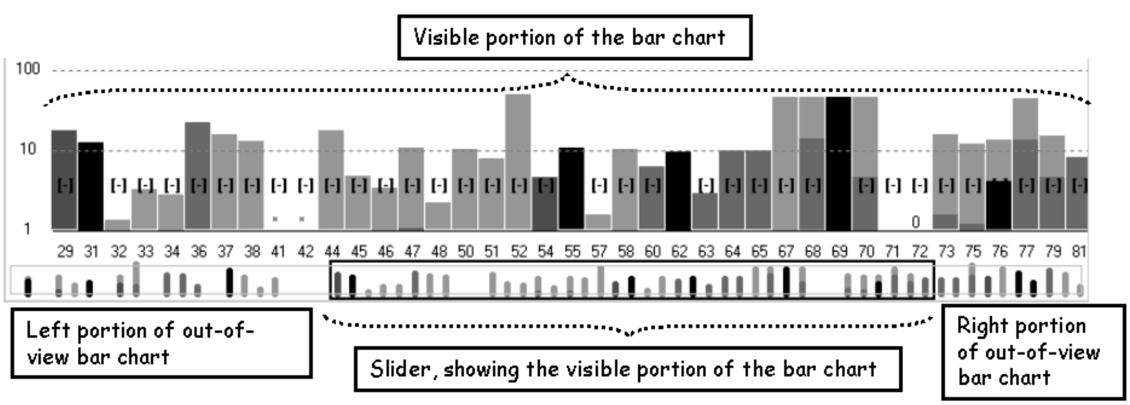

Figure 9. Thumbnail slider control for large bar charts

lower bound for the desired benefit. Then, the optimization problem becomes meeting the benefit lower bound and determining the minimum cost to accomplish that.

The DDP tool offers an heuristic search capability that uses a simulated annealing process to locate near-optimal solutions (where the meaning of optimal is set by the user). DDP can perform a series of such searches to reveal the overall cost/benefit trade space – the so-called "Pareto frontier" [6]. A visualization of the results of a series of such searches calculated for a recent TIMA study is shown in Figure 10. This study involved 58 PACTs, for which the number of possible selections is 2^{58} (approximately 10^{18}). The grand total cost of applying all 58 PACTs exceeds $4M. Figure 10 shows, that as the cost increases towards the $1M level, benefit attainment increases dramatically, but then benefit attainment quickly asymptotes above the $1M mark. Most of the benefit will have been attained at an investment level of about $1.2M at which point, the law of diminishing returns is manifest. Experts who are involved in TIMA studies can use the results of such heuristic searches to guide their decisions in selecting optimal PACT sets. Individual near-optimal PACT set solutions (as found by the simulated annealing optimizer process) can be examined using the DDP software and then tuned as needed.

Input from experts provides the data on which to base the calculations. An automated search routine is used to explore the large option space. Visualization is used to present the results to the experts. The experts use these results as a guide for final decision making. This process is an instance of software-assisted decision-making.

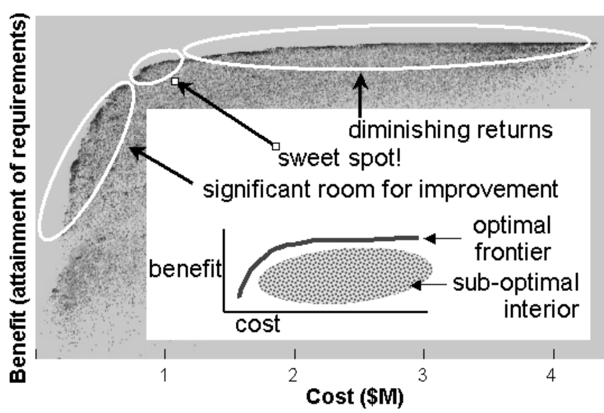

Figure 10. Cost/benefit trade space

7. Conclusions

A Technology Infusion Maturity Assessment (TIMA) process has been developed at JPL to address impediments to infusing new technology on future space exploration missions. Like many decision-making steps involved in spacecraft development, the TIMA process combines human expertise, an appropriate input-feedback process, and software support to help experts reach a consensus on a well-reasoned development approach. This paper has focused on describing the custom software tool, DDP, that was developed to support the TIMA process, and on showing how the needs of the TIMA process have influenced the development of the structure and capabilities of the DDP software. The DDP tool now combines a highly flexible graphical user interface to support the TIMA process, a set of appropriate data representations coupled with data processing efficiency measures to ensure rapid responsiveness in a DDP-user environment, a variety of visualization templates to effectively present the data, and heuristic search techniques to guide experts in making technology-infusion-related decisions. The overall goal of the TIMA process and it's DDP software support tool is to provide a systematic approach for gathering, compiling, processing, and presenting information in a way that will enhance the successful infusion of new technology into future spacecraft missions.

8. Acknowledgements

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